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**NPG Report No. 1535**

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**DIRECT CONTACT EXPLOSION EFFECTS ON  
ORDNANCE MATERIALS - TESTS ON MILD STEEL, STS ARMOR AND  
2024-T4 ALUMINUM ALLOY PLATES 1-1/2 INCHES THICK**

**FC**



**U. S. NAVAL PROVING GROUND  
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Direct Contact Explosion Effect on  
Ordnance Materials - Tests on Mild Steel, STS Armor and  
2024-T4 Aluminum Alloy Plates 1-1/2 Inches Thick

by


H. E. Romine  
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NPG REPORT NO. 1535

Foundational Research Project  
NPG-T-1801-4

29 April 1957

APPROVED: G. H. WALES  
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Captain, USN  
Ordnance Officer  
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- A. Explosion and Tensile Test Data (Tables 1 and 2)
- B. Sketches, Graphs and Photographs (Figures 1-16)
- C. Distribution



ABSTRACT

A test has been developed for comparing resistance of materials such as armor plate against direct attack by high explosive. Impacts were made on 1-1/2 inch thick plates of mild steel, STS armor and 2024-T4 aluminum alloy. At this thickness level, STS was most resistant to fracture, followed by mild steel and aluminum alloy in decreasing order of merit. Direct attack implies a solid-to-solid contact between explosive and test material. A shock wave developed in a small candle of high explosive was transmitted to the test surface through a measured thickness of plastic acting as a gap degrader. The degrading effect was controllable so that a shock could be identified which was just sufficient to initiate internal cracking. Some particulars of shock wave behavior were deduced from a study of sectioned impacts.

**FOREWORD**

This investigation was made under Naval Proving Ground Foundational Research Project No. NPG-T-1801-4, "Impact Performance of Ordnance Materials". The tests were carried out in the period from June 1954 to June 1956.

The application of the gap degrader principle was based upon suggestions made by Dr. S. J. Jacobs, Chief of Detonation Division, Naval Ordnance Laboratory (reference (a)). The explosive impacts and ultrasonic inspections were conducted by LTJG J. W. Gorman, Firing Officer, Naval Proving Ground. The illustrations were prepared by Mrs. E. P. Berry.

This report was reviewed for technical accuracy by:

W. W. MEYERS, Head, Development Division  
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Damage ratings after explosive attack can be based upon comparison of bulges or scabs produced at the back of the plate. This type of failure includes both initiation and propagation of fracture. A criterion of initiation fracture only was sought in the present method to simplify evaluation. Initiation of internal fracture was determined approximately by means of ultrasonic inspection and confirmed by sectioning critical impacts.

The mechanism of internal fracture in direct explosion attack is relatively simple at a first approximation. The initial elastic compression wave reflects as a tension wave from the back surface and acquires maximum tensile effect after it has returned past interference from the remainder of the oncoming elastic compression wave. This distance is about half a wave length measured from the back of the plate. If free tension exceeds the material strength it will cause internal fracture. The strength criterion is a dynamic property and was designated "critical normal fracture stress" in reference (b).

Shock wave phenomena appear more difficult on further analysis. Besides the elastic compression wave and its reflection, there is a slower plastic wave. Rebound of the face after explosion creates additional tension waves (reference (c)). The existence of "tension tails" to expanding compression waves has been shown in reference (d). A theoretical study in reference (e) postulated five distinct regions in the wave before reflection. Numerous reflections and interactions of these waves are possible.

Since the present study was directed mainly toward a comparison of materials, impulsive loading phenomena were not investigated directly. However, some interesting effects are described which took place as a result of diminishing shock through the range of fracture initiation.

#### DESCRIPTION OF MATERIAL

Three materials were tested in the same plate thickness of 1-1/2 inches: mild steel, STS armor and 2024-T4 aluminum alloy. The plates were taken from stock at the Naval Proving Ground; the quality was believed to be average for the grade. The steel compositions were as follows:

	<u>C</u> <u>(%)</u>	<u>Mn</u> <u>(%)</u>	<u>P</u> <u>(%)</u>	<u>S</u> <u>(%)</u>	<u>Si</u> <u>(%)</u>	<u>Ni</u> <u>(%)</u>	<u>Cr</u> <u>(%)</u>
Mild steel	0.23	0.48	0.036	0.039	0.08	-	-
STS armor	0.30	0.16	0.011	0.020	0.09	3.12	1.32

The 2024-T4 aluminum plate was not analyzed but the nominal alloy content is 4.5 percent copper, 0.6 percent manganese and 1.5 percent magnesium. Some physical properties are described later.

#### DESCRIPTION OF TEST EQUIPMENT AND PROCEDURE

The method of applying a shock impulse is illustrated in Figure 1. The explosive candle was a cardboard tube container packed with 0.27 pound of composition C-4 plastic high explosive, using care to produce uniformity in a series of charges.

A critical feature of the test is the preparation of precision-molded plastic disk degraders of variable thickness and a high degree of surface flatness. The mold design shown in Figure 2 was based on an English technique for pressing flat disks described in reference (f).

"At room temperature the diameter of the aluminum disks is slightly less than the internal diameter of the cylinder but due to aluminum having a larger coefficient of expansion than steel, the aluminum disk diameter is slightly greater at the molding temperature, about 250°C. The aluminum disks therefore act as a seal preventing the material exuding into the annular gap between the piston and cylinder while the material is molded.... The disks, with the specimen sandwiched between them, are easily removed from the cold mold and are then sheared off the specimen."

The tight seal enabled close control of disk thickness by weighing the charge of molding compound. The two-inch diameter disks ranged from 1/8 to 5/8 inch in thickness; larger standoffs were obtained by stacking. The molding compound was medium flow Tenite acetate (Tenite I) designated 036A-29873-M, clear transparent. A trial lot was supplied gratis for development work by Eastman Chemical Products, Inc., Kingsport, Tennessee. The hardness of the molded plastic was approximately 75 Rockwell R. After light rubbing on fine emery paper, the disks were flat

within a few thousandths of an inch. A thin film of silicone stopcock grease was applied to hold stacked disks together and onto the plate surface. Stacking disks for large standoff is believed to have introduced no serious side effects other than changing thickness. It has been verified experimentally that built-in interfaces do not materially alter compression waves (reference (d)).

The 1-1/2 inch thick test plates were cut approximately 8 inches wide by 24 inches long and the longitudinal edges were ground or machined smooth to provide a good surface for application of the ultrasonic searching unit. The steel plates required light face grinding to provide a smooth surface for attaching plastic disks. The aluminum plate surface was sufficiently smooth without grinding. In making an explosion test, the plate was held level and supported around the edges of the explosion area by square bars laid on a heavy armor plate base.

A test series was started with a close standoff which allowed a substantial bulge to form on the back of the plate. Subsequent impacts were made at increasing standoffs and the bulge gradually disappeared. From then on the impacted zone was inspected ultrasonically after each explosion. A Sperry type UR reflectoscope was used as shown in Figure 3. Part of the ultrasonic energy was reflected from the internally damaged zone behind an impact and appeared as "pips" on the reflectoscope screen, Figure 4. Reduction in pip height was gradual as plastic standoff increased until only small remaining pips suggested that internal fracture had ceased. The worked metal without fracture produced some reflection. A series was concluded when it was believed that standoff had been increased to a thickness sufficient to prevent internal cracks. All tests were made at ambient temperature.

## RESULTS AND DISCUSSION

### Impact Effects

Data on the individual explosions are listed in Table 1 and the faces of impacted plates are shown in Figure 5. Macrostructures and hardness patterns of sectioned impacts are illustrated in Figures 6, 7 and 8. The shaded part of a hardness pattern extends over the zone where hardness had been increased definitely above that of the base metal. The

zone is a probable indication of the extent of heavy deformation produced by a plastic shock wave. Conversely, zones showing no serious work-hardening in the path of an impulse are considered to have been traversed by elastic waves only.

In the hardness patterns corresponding to first appearance of internal cracks in STS (Figure 7, 0.70 inch standoff) and aluminum alloy (Figure 8, 1.52 inch standoff) the cold-worked zones are separated from the fractures by unworked metal. This is believed to show that the initial fractures resulted from elastic wave action alone and is a confirmation of the reflected wave theory. At lower standoffs where scab fracture existed, the work-hardened zone tended to overlap fractures and it is not certain that scab fracture was caused entirely by elastic reaction. Mild steel in Figure 6 did not show the same relation between work-hardening and fracture because the plastic wave appeared to have traveled much faster in relation to the elastic wave. It will be shown under microstructure that mild steel underwent a special type of plastic deformation from shock known as mechanical twinning. Twinning permits plastic deformation with smaller relative atom movement than slip and therefore it could be expected to proceed at a faster rate than ordinary slip deformation.

Internal fracture changes correlated with decreasing standoff in Figures 6, 7, 8 and 9 revealed that crack initiation occurred at a distance from the back surface greater than the thickness of the scab layer which, at less standoff, lifted and formed a bulge. The relation between these two locations of internal cracking was not clear, apparently they coexisted at low standoff. The contingency must be considered that the dual fracture locations may have been some peculiarity of the method of testing.

Input of shock energy should be some function of standoff distance; therefore, a general comparison was made of all three plates on the basis of standoff in Figure 10. It was evident that STS had greater resistance to internal fracture than the same thickness of mild steel or aluminum alloy. Comparing only the latter two, mild steel showed a slight superiority on a basis of equal thickness. This investigation is being continued to determine the relative performance of these materials at the same weight per square foot.

### Tensile Properties

The sketch in Figure 11 shows that tensile properties were measured at a position close to that of the shock fractures. Special tensile tests were made in the thickness direction since the fractures would be similar in orientation to initiation or scabbing fractures. The results are given in Table 2.

Reduction of area in the thickness direction is an important measure of ductility in the direction of the principal stress from the shock wave. This value was relatively high in all three plates, being about four-tenths of the corresponding values from standard longitudinal and transverse tests. STS in particular had a high value of 29 percent reduction in area (thickness). This resulted partly from a condition of good steel cleanliness confirmed later by the microstructure. The thickness tests also gave superior nominal tensile strength values for notched over unnotched specimens. This indicated desirable insensitivity to notch brittleness at the ambient test temperature. The STS steel again had a very good value for this ratio.

Relating tensile data to the steels in Figures 6 and 7, it was noted that both mild steel and STS had about the same thickness of scab layer and depth of initiation fracture notwithstanding the great difference in tensile strength. Aluminum fractures in Figures 8 and 9, however, showed a greater relative depth of both layers although the strength was about that of mild steel.

### Microstructure

Impacts which gave initiation fractures only were examined and the photomicrographs are shown in Figures 12 and 13. The typical fracture was composed of flat steps or breaks parallel to the plate surface and joined together by irregular shear fractures.

Inclusions, if associated at all with direct explosion fracture, must have been only such that chanced to be directly in the fracture path. Adjacent inclusions in the highly stressed fracture zone showed practically no evidence of separation, Figure 12 and Figure 13(B). The STS, Figure 13(A), was found to be an exceptionally clean steel almost free from inclusions.

The etched microstructures in Figures 14 and 15 depict explosive impact effects on metal grain structure. The well-known mechanical twins or Neumann bands associated with shock deformation of ferrite were present in the mild steel (Figure 14). It has been mentioned that shock twinning may explain a unique property of high plastic wave velocity in mild steel deduced from the hardness patterns of sectioned impacts. The STS plate (Figure 15(A)) had a quenched and tempered structure with no evidence of shock twinning even in minute ferrite grains near the impact face. The grain structure of the aluminum alloy in Figure 15(B) likewise gave no visible evidence of special effects from shock deformation.

#### Comparison with Squash-Head Attack

A section through a simulated squash-head impact on 5-inch Class B armor (similar to STS) was available from another Naval Proving Ground project. It is interesting to note that the scab on the 1-1/2 inch STS plate of Figure 7 and the scab on the 5-inch plate shown in Figure 16 both have similar characteristics.

#### CONCLUSIONS

As a result of the investigation conducted, it is concluded that:

a. Materials may be compared for resistance to internal fracture from direct explosive attack by using a fixed charge of explosive from which shock is conducted to the material surface through a measured thickness of plastic acting as a gap degrader.

b. At the same 1-1/2 inch thickness level, the materials in decreasing order of resistance to internal fracture resulting from direct explosion impact were STS, mild steel and 2024-T4 aluminum alloy.

c. The use of precision-molded plastic disks as degrading elements introduced a degree of control into the test so that a shock could be identified which would just initiate internal cracking.



d. There was some indication that internal cracking may have been initiated at a greater distance from the back surface than scabbing fracture.

#### REFERENCES

- (a) Presentation by Dr. S. J. Jacobs at the Bureau of Ships Direct Explosion Test Advisory Committee Meeting, 15 January 1952 and discussion at NOL on 4 November 1953.
- (b) Rinehart, J. S., "Some Quantitative Data Bearing on the Scabbing of Metals Under Explosive Attack", Journal of Applied Physics, Vol. 22, No. 5, p. 555 (1951).
- (c) Muller, A., Benz, W. G., Snelling, W. A., Saibel, E., "Final Report on Application of the Explosive Test to Evaluate Shock Properties of High Yield Strength Steels", Ship Structure Committee Report Serial No. SSC-29 (1949).
- (d) Cassity, C. R., Gourley, L. E., Kempton, M. L., "Aircraft Damage Studies", New Mexico Institute of Mining and Technology, Research and Development Division, Conf Quarterly Report No. T-919, Contract NOrd 13348 (1955).
- (e) Huth, J. H., Cole, J. D., "A Theoretical Treatment of Spalling", U. S. Air Force Project Rand RM-1181 (1954).
- (f) Stark, K. H., Note on "Mold for Pressing Plastic Disks", Journal of Scientific Instruments (British), Vol. 30, p. 341 (1953).

APPENDIX A

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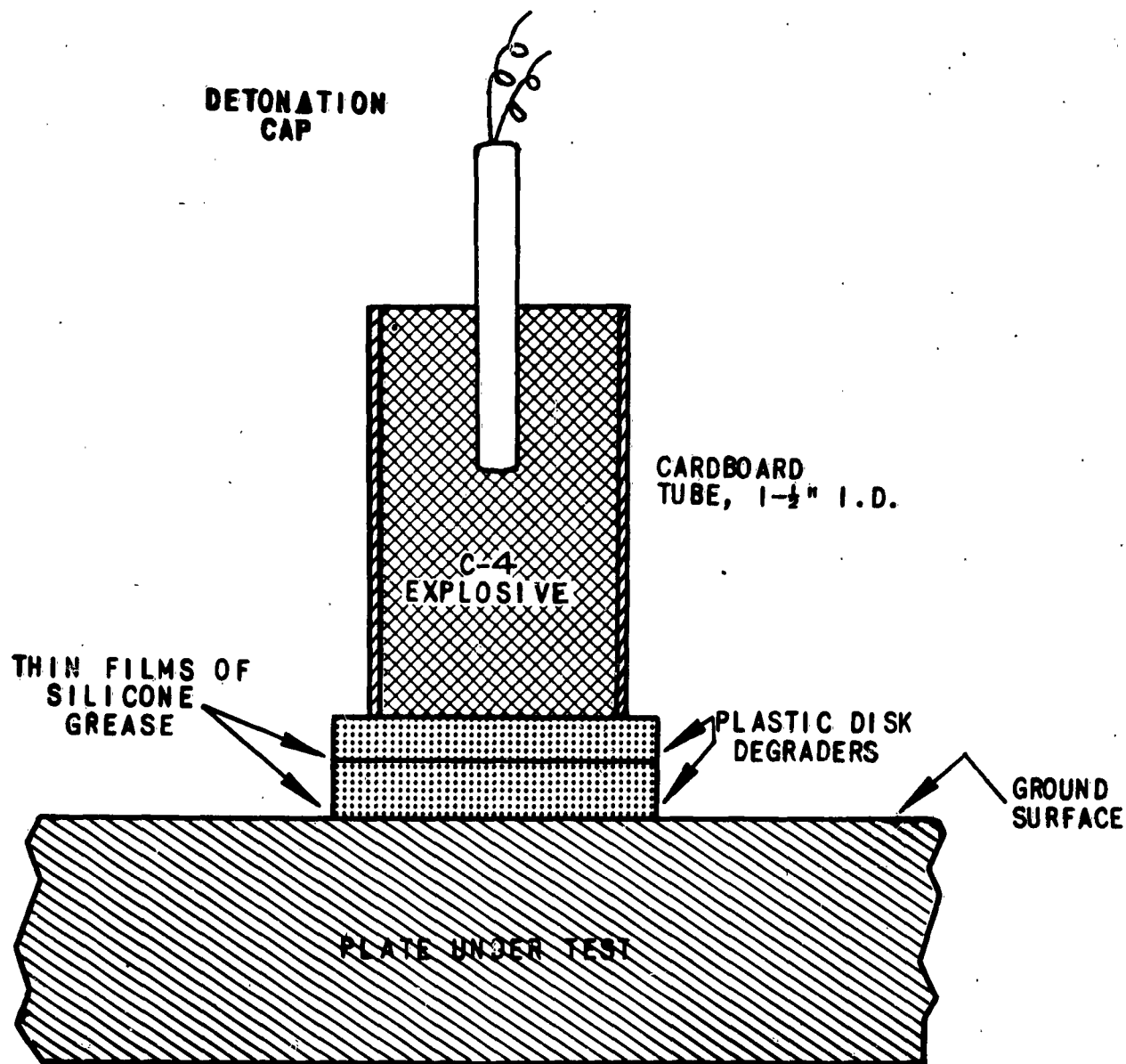
TABLE 1  
RECORD OF DIRECT-CONTACT EXPLOSION TESTS

Blast Number	Material Under Test		Explosive Charge		Plastic Standoff (in)	Test Temperature	Notes
	Type	Thickness (in)	Type	Weight (lb)			
54-6-14-1	STS Armor	1.5	Comp. C-4	0.27	0.25	Ambient (80° F)	Bulge, no spall.
54-6-14-2	STS Armor	1.5	Comp. C-4	0.27	0.50	Ambient (80° F)	Slight bulge, no spall.
54-6-14-3	STS Armor	1.5	Comp. C-4	0.27	0.63	Ambient (80° F)	
54-6-29-1	STS Armor	1.5	Comp. C-4	0.27	0.76	Ambient (80° F)	
54-6-29-2	STS Armor	1.5	Comp. C-4	0.27	0.85	Ambient (80° F)	
54-9-2-3	Mild Steel	1.5	Comp. C-4	0.27	0.50	Ambient (80° F)	Bulge, no spall.
54-9-2-4	Mild Steel	1.5	Comp. C-4	0.27	0.70	Ambient (80° F)	Bulge, no spall.
54-9-2-5	Mild Steel	1.5	Comp. C-4	0.27	1.15	Ambient (80° F)	
54-9-29-1	Mild Steel	1.5	Comp. C-4	0.27	1.28	Ambient (80° F)	
54-10-1-1	Mild Steel	1.5	Comp. C-4	0.27	1.47	Ambient (90° F)	
54-12-22-1	Aluminum 2024-T4	1.5	Comp. C-4	0.27	0.77	Ambient (30° F)	Bulge cracked, no spall.
54-12-22-2	Aluminum 2024-T4	1.5	Comp. C-4	0.27	1.00	Ambient (30° F)	Slight bulge, no spall.
54-12-22-3	Aluminum 2024-T4	1.5	Comp. C-4	0.27	1.30	Ambient (30° F)	
55-1-6-1	Aluminum 2024-T4	1.5	Comp. C-4	0.27	1.52	Ambient (30° F)	
55-1-6-2	Aluminum 2024-T4	1.5	Comp. C-4	0.27	1.76	Ambient (30° F)	

(1) A thin film of silicone grease was used to hold plastic disks together and onto metal surface.

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APPENDIX B

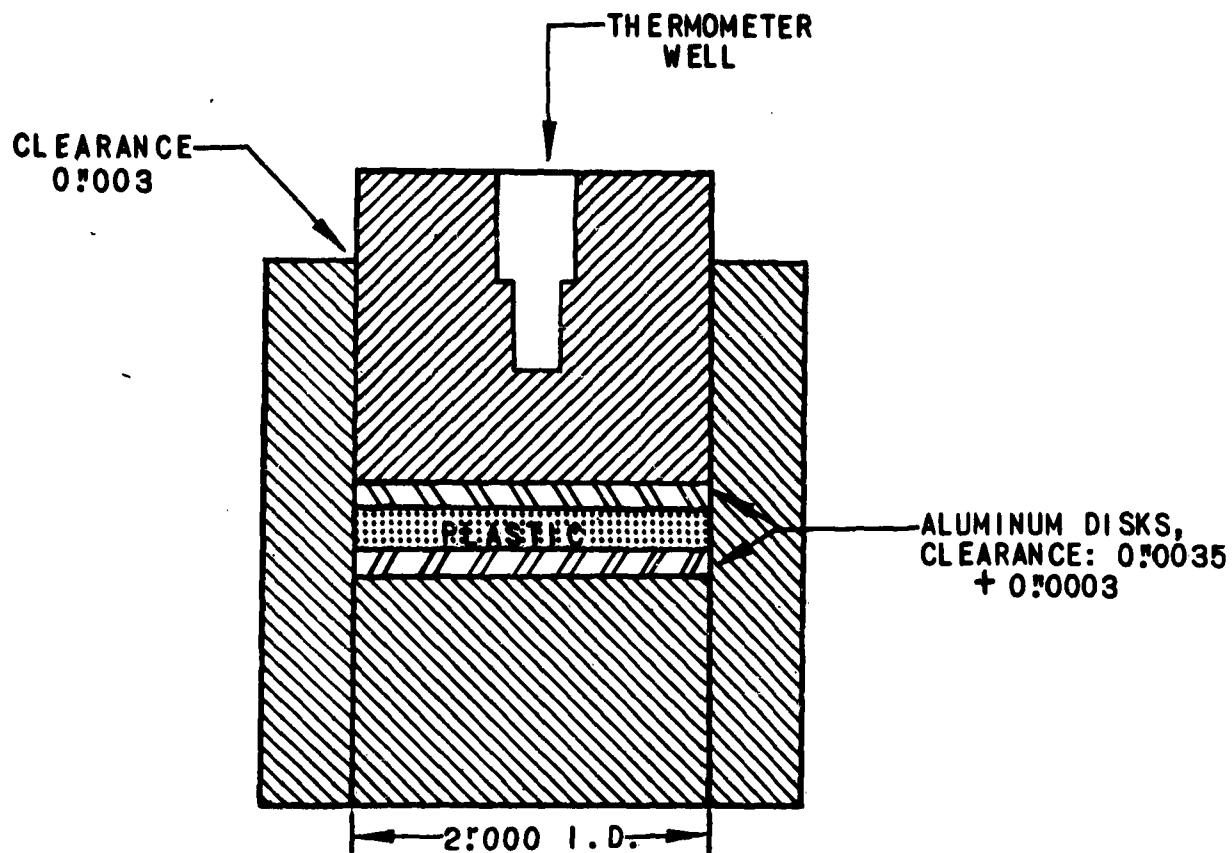


Scale: Actual Size

SECTION THROUGH CLOSE CONTACT  
EXPLOSIVE TEST FOR INTERNAL  
SEPARATION OF ARMOR PLATE

Figure 1

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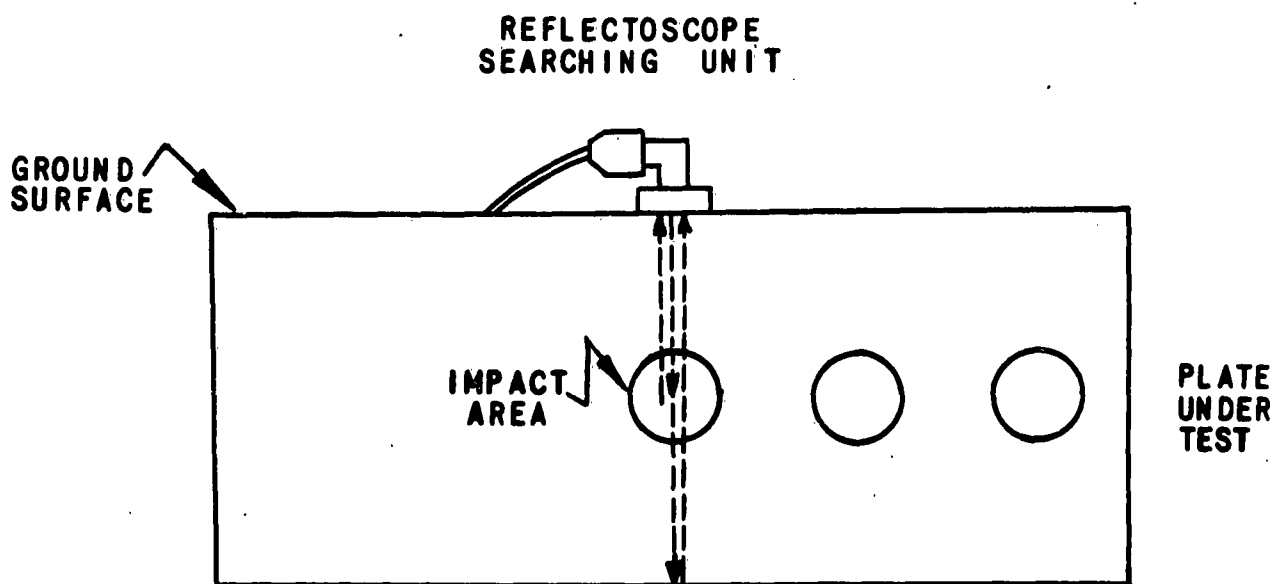
Scale: Actual Size

# SECTIONAL VIEW OF MOLD FOR MAKING PRECISION PLASTIC DISK DEGRADERS

Plastic Cavity Sealed by Differential  
Expansion of Aluminum Disks.

Figure 2

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Reduced Scale: 2" = 8"

ULTRASONIC REFLECTOSCOPE EXAMINATION  
FOR INITIATION OF INTERNAL FRACTURE

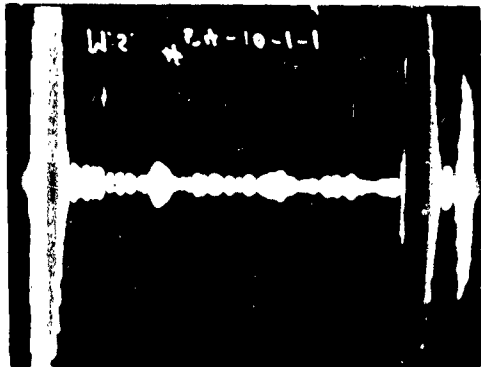
FIGURE 3

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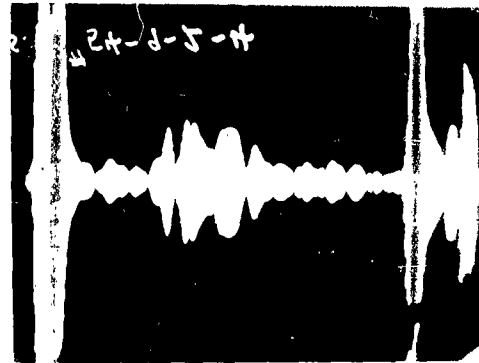
FACE CENTRAL BACK  
PIPS REFLECTION

FACE CENTRAL BACK  
PIPS REFLECTION

MILD  
STEEL

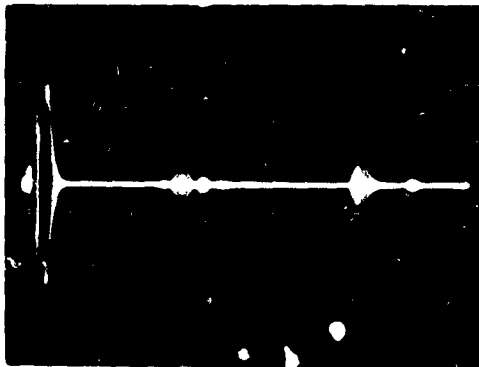


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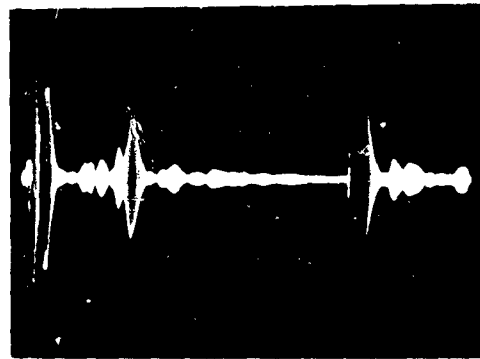


0:70

STS  
ARMOR

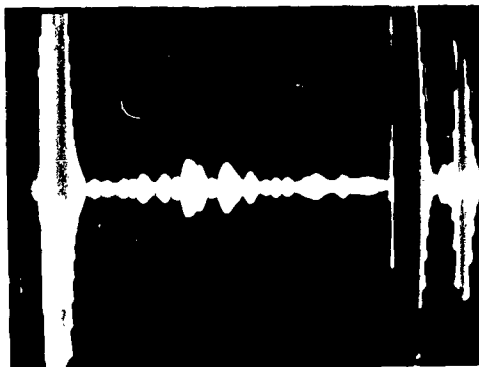


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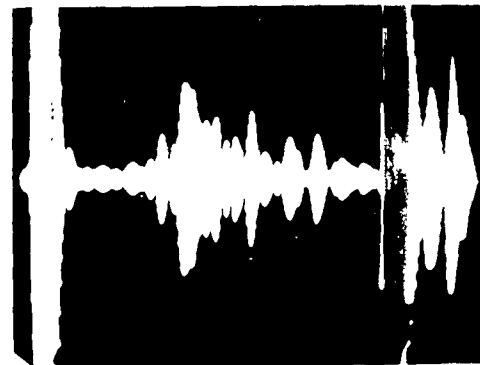


0:80

2024-T4  
ALUMINUM



1:76



1:00

STANDOFF GREATER THAN  
INITIATION DISTANCE

Small Pips Show Little  
Internal Damage

STANDOFF LESS THAN  
INITIATION DISTANCE

Larger Pips Indicate  
Heavier Internal Damage

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TYPICAL ULTRASONIC REFLECTOGRAMS USED AS  
TESTS FOR INTERNAL DAMAGE

FIGURE 4





FACE OF PLATES SHOWING AREAS OF DIRECT EXPLOSION IMPACT

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FIGURE 5

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MACROSECTIONS AND HARDNESS DISTRIBUTIONS  
IN DIRECT EXPLOSION TESTS AGAINST 1-1/2"  
THICK PLATE OF MILD STEEL

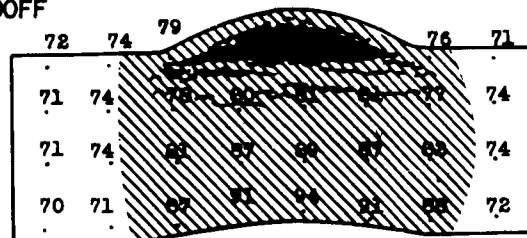
SHADED AREAS REPRESENT HARDNESS

OF 75 R<sub>B</sub> OR OVER

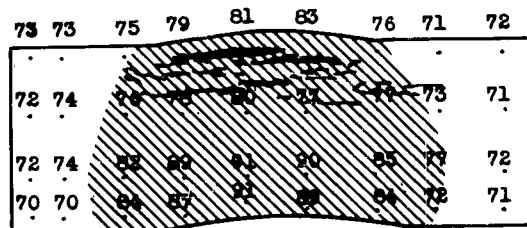
PLASTIC STANDOFF



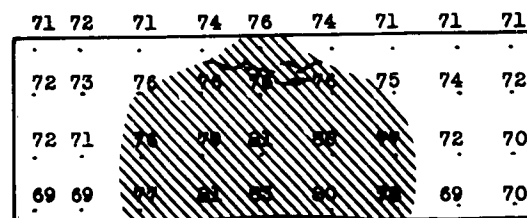
0.50



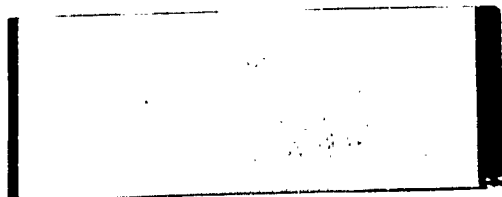
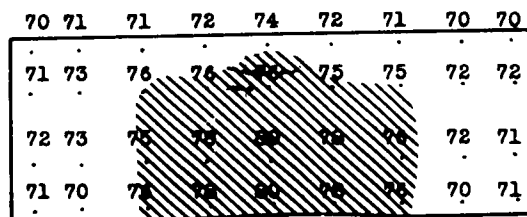
0.70



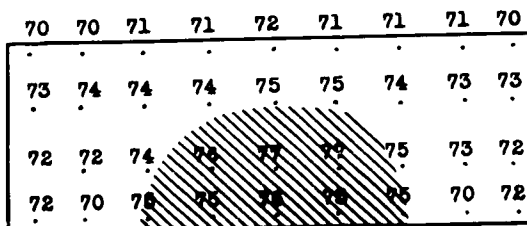
1.15



1.28

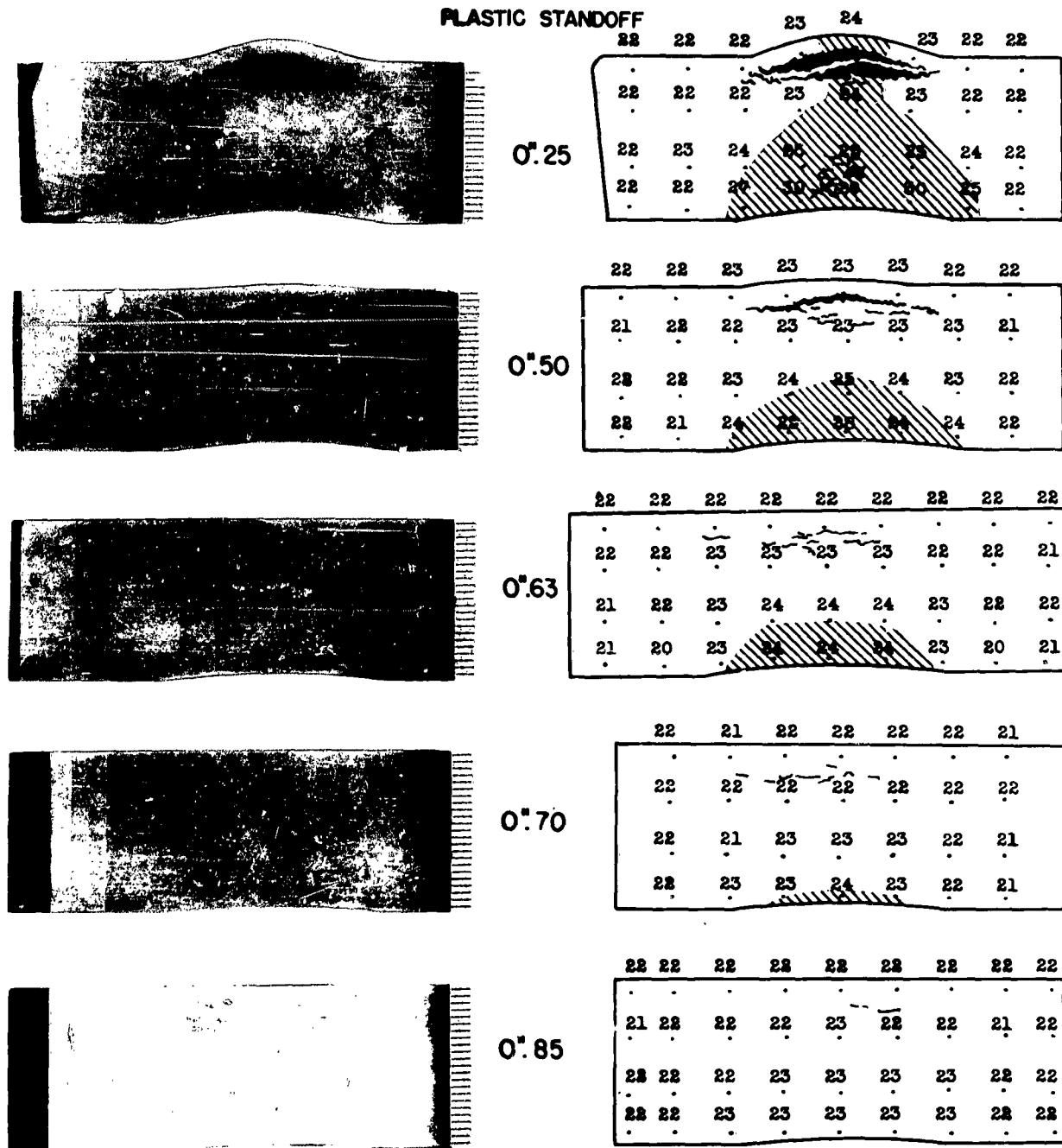


1.47



MACROSECTIONS AND HARDNESS DISTRIBUTIONS  
IN DIRECT EXPLOSION TESTS AGAINST 1-1/2"  
THICK PLATE OF SPECIAL TREATMENT STEEL

SHADED AREAS REPRESENT HARDNESS  
OF 24 R<sub>C</sub> OR OVER



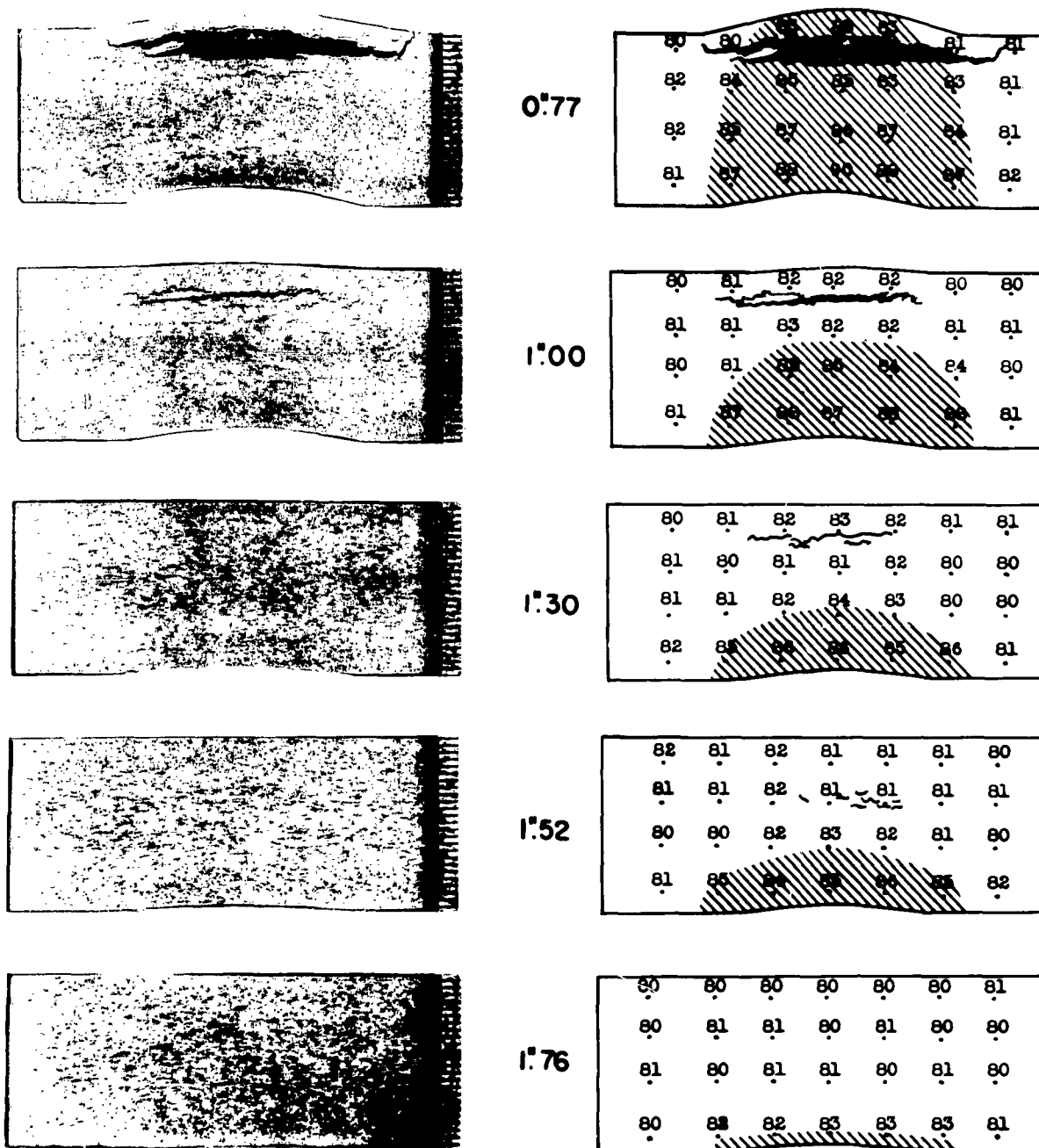
NP9-68787  
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FIGURE 7

MACROSECTIONS AND HARDNESS DISTRIBUTIONS  
IN DIRECT EXPLOSION TESTS AGAINST 1-1/2"  
THICK PLATE OF 2024-T4 ALUMINUM ALLOY

SHADED AREAS REPRESENT HARDNESS  
OF 83 R<sub>B</sub> OR OVER

PLASTIC STANDOFF



NP9-68786

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FINE CRACKS BASED ON DYE PENETRANT TEST

FIGURE 8

PLASTIC  
STANDOFF  
(IN)

0.77

1.00

1.30

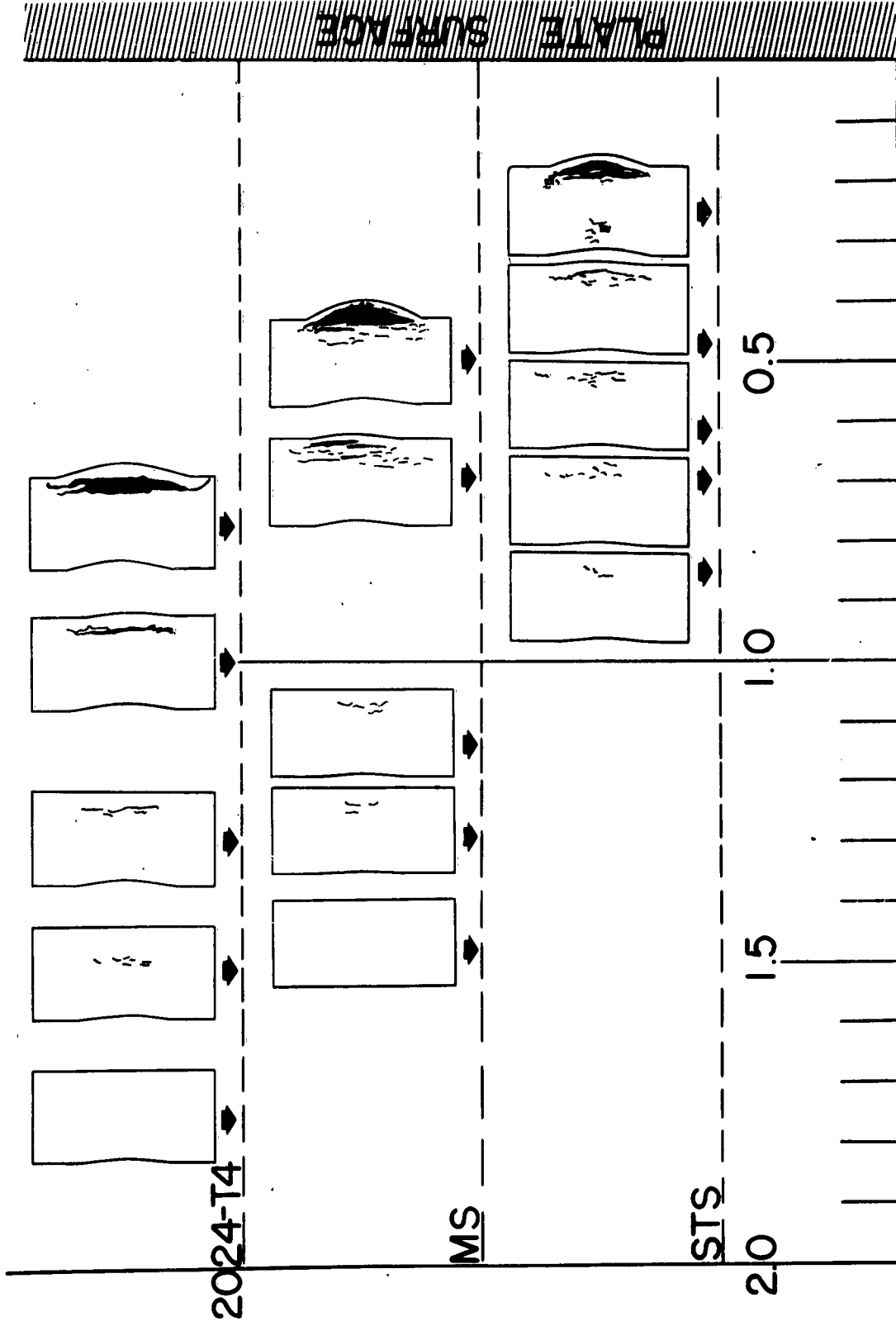
1.52

1.76

2024-T4 ALUMINUM ALLOY SECTIONS AFTER SPOTCHECK DYE PENETRANT TEST

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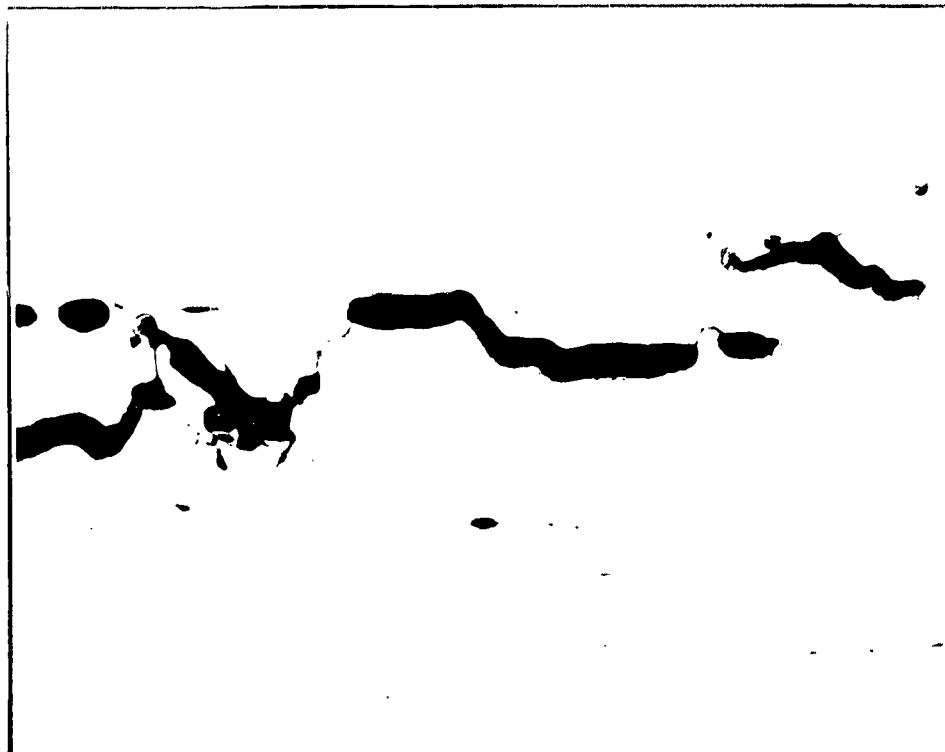
FIGURE 9



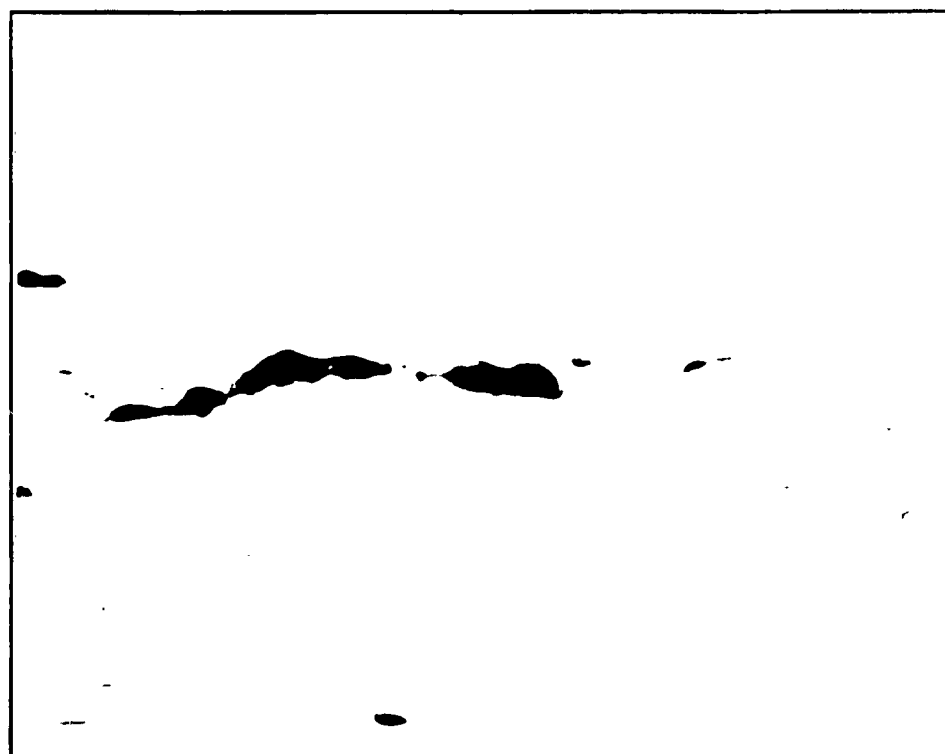
PLASTIC STANDOFF - (IN)

COMPARATIVE SKETCHES OF DAMAGE RESULTING FROM DIRECT EXPLOSION  
TESTS AGAINST 2024-T4 ALUMINUM, MILD STEEL AND STS ARMOR  
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FIGURE 10



(A)

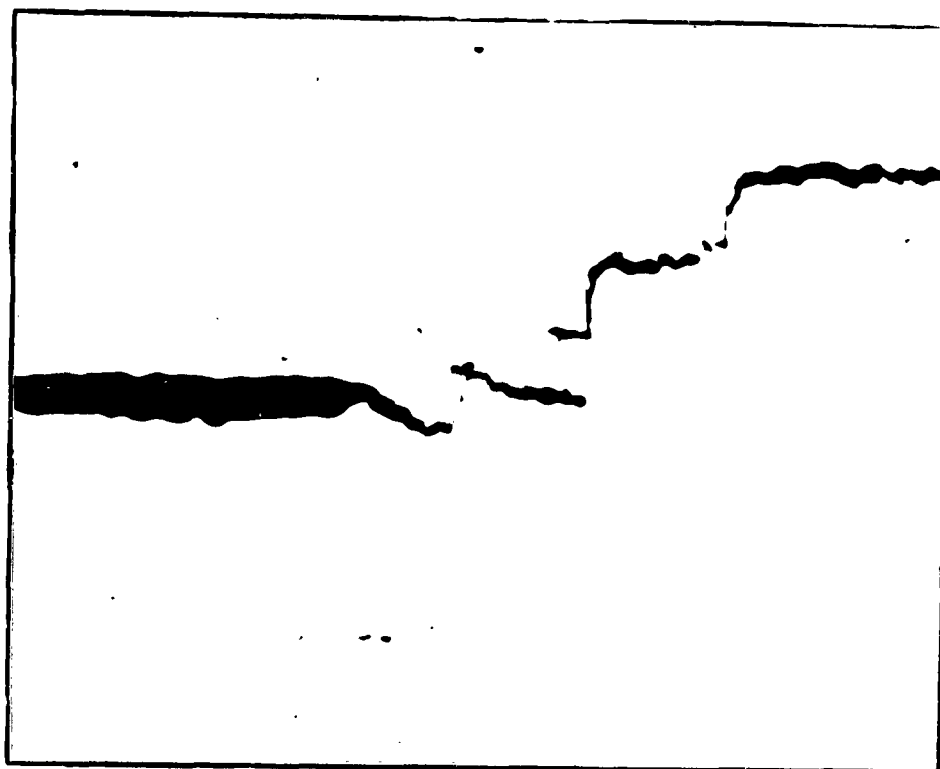


(B)

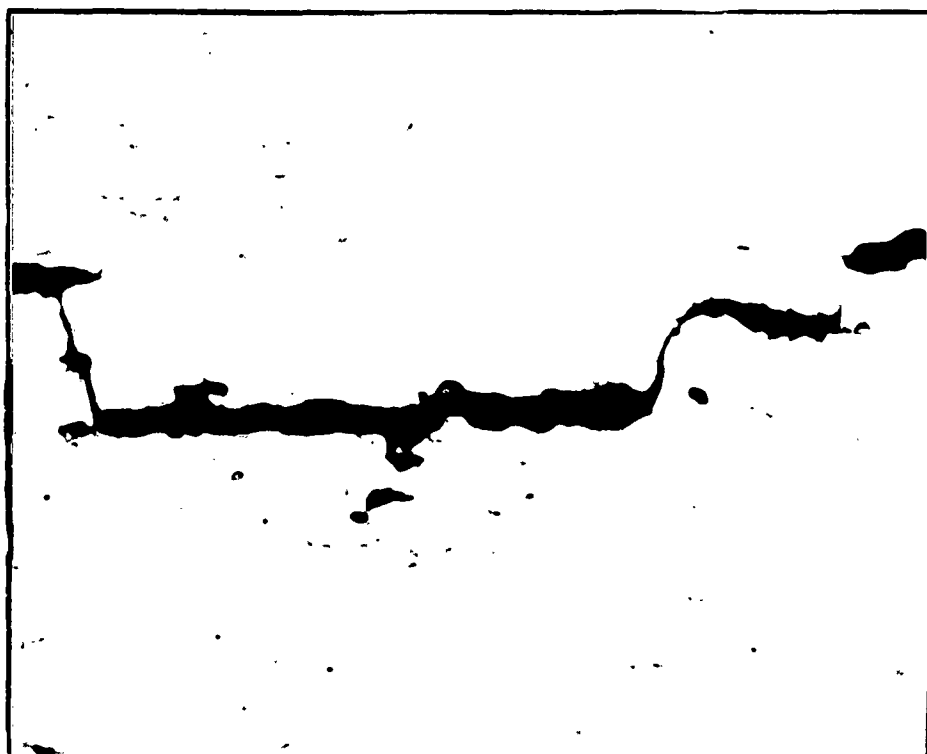
INITIATION FRACTURES IN MILD STEEL  
UNETCHED, X200

PHD-71646  
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FIGURE 12



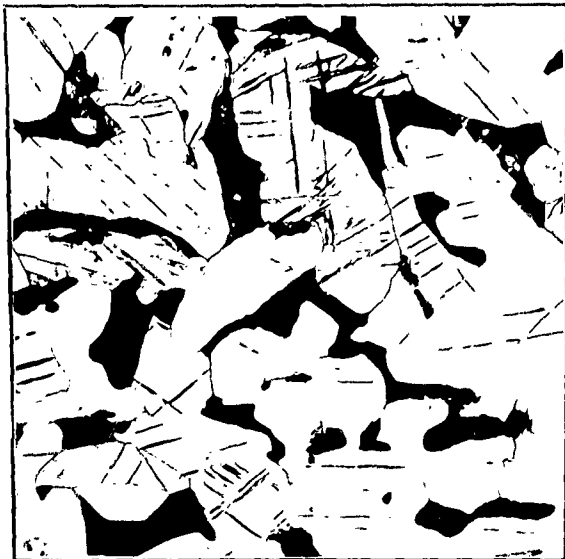
(A) STS ARMOR



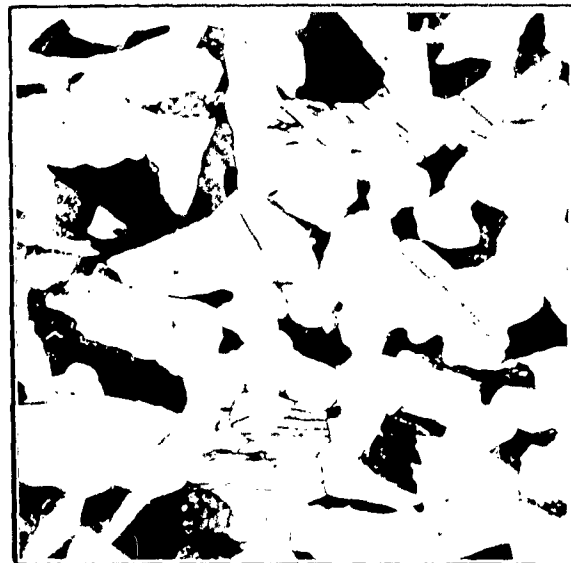
(B) 2024-T4 ALUMINUM ALLOY

TYPICAL INITIATION FRACTURES  
UNETCHED, X200

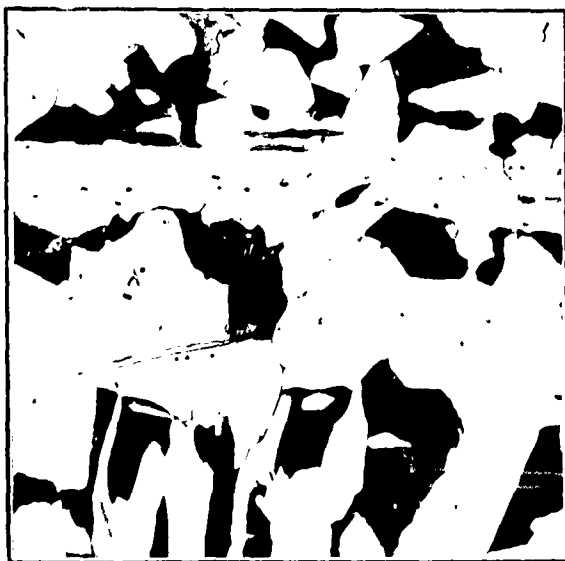




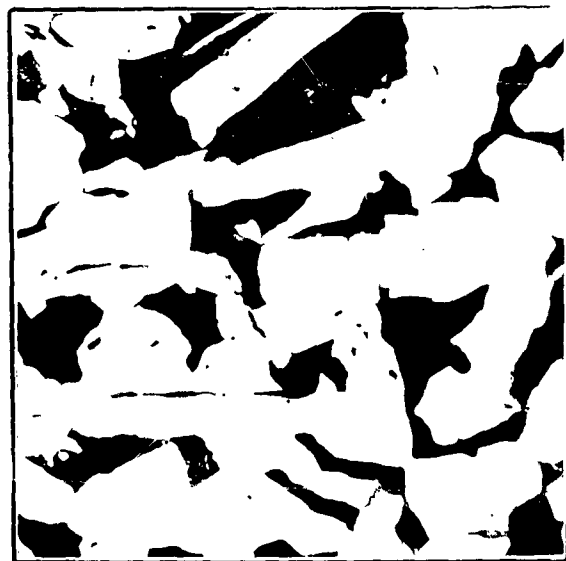
(A) DIRECTLY UNDER  
IMPACT AT FACE



(B) 3/8 INCH BEHIND  
FACE



(C) 3/4 INCH BEHIND  
FACE



(D) 1-1/2 INCH BEHIND  
FACE, BACK OF PLATE

MILD STEEL MICROSTRUCTURES SHOWING DIMINISHED  
MECHANICAL TWINNING WITH INCREASED DISTANCE  
FROM IMPACTED FACE OF PLATE, 1"28 STANDOFF  
NITAL-PICRAL ETCH, X200

PHD-71648  
CONFIDENTIAL

FIGURE 14



(A) STS ARMOR, 0.76 STANDOFF  
NITAL-PICRAL ETCH, X1000



(B) 2024-T4 ALUMINUM ALLOY,  
1.52 STANDOFF  
KELLER'S ETCH, X250

MICROSTRUCTURE AT IMPACT FACE



Actual Size

SECTION THROUGH SCAB FORMED IN CLASS B ARMOR FIVE INCHES THICK  
BY SIMULATED ATTACK WITH A SQUASH HEAD PROJECTILE

Two Pounds of Explosive Were Formed to the Squashed Shape  
and Statically Detonated on the Plate Surface.

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FIGURE 16

APPENDIX C

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<p>Naval Proving Ground. (NPG Report No. 1535) DIRECT CONTACT EXPLOSION EFFECT ON ORDNANCE MATERIALS - TESTS ON MILD STEEL, STS ARMOR AND 2024-T4 ALUMINUM ALLOY PLATES 1½ INCHES THICK, by H. E. Romine. 29 Apr 1957. 8 p. 16 figs.</p> <p>Impacts were made on 1½ inch thick plates. At this thickness level, STS was most resis- tant to fracture, followed by mild steel and aluminum alloy in decreasing order of merit. A shock wave developed in a small candle of high explosive was transmitted to the test surface through a measured thickness of plastic acting as a gap degrader. The de- grading effect was controllable to permit a shock just sufficient to initiate internal cracking.</p> <p>CONFIDENTIAL</p>	<p>1. Armor plate - Vulnerability 2. Explosives - Effectiveness I. Romine, H. E.</p> <p>Task: Foundational Research Project NPG-T-180 I-4</p> <p>CONFIDENTIAL</p>	<p>Naval Proving Ground. (NPG Report No. 1535) DIRECT CONTACT EXPLOSION EFFECT ON ORDNANCE MATERIALS - TESTS ON MILD STEEL, STS ARMOR AND 2024-T4 ALUMINUM ALLOY PLATES 1½ INCHES THICK, by H. E. Romine. 29 Apr 1957. 8 p. 16 figs.</p> <p>Impacts were made on 1½ inch thick plates. At this thickness level, STS was most resis- tant to fracture, followed by mild steel and aluminum alloy in decreasing order of merit. A shock wave developed in a small candle of high explosive was transmitted to the test surface through a measured thickness of plastic acting as a gap degrader. The de- grading effect was controllable to permit a shock just sufficient to initiate internal cracking.</p> <p>CONFIDENTIAL</p>	<p>1. Armor plate - Vulnerability 2. Explosives - Effectiveness I. Romine, H. E.</p> <p>Task: Foundational Research Project NPG-T-180 I-4</p> <p>CONFIDENTIAL</p>	<p>1. Armor plate - Vulnerability 2. Explosives - Effectiveness I. Romine, H. E.</p> <p>Task: Foundational Research Project NPG-T-180 I-4</p> <p>CONFIDENTIAL</p>
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ARMOR AND 2024-T4 ALUMINUM ALLOY PLATES 1-1/2 INCHES THICK. NPG REPORT NO. 1535